A Flexible Quasi-Optical System for Polarimetric Submillimeter-Wave Reflectometry

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Abstract—**First measurements of the reflectivity of different natural and artificial materials in the 600 GHz range are reported. The investigations were carried out using a heterodyne broadband dual-polarization reflectometer which was realized in a flexible quasi-optical technique. This special construction allows the design to be changed very quickly according to the desired measurement task. The design principles of this setup are presented.**

Compared to Fourier-transform spectrometers the described reflectometer is capable to carry out real-time measurements even outside the laboratory. Reflectivity data of several interesting materials are presented in co- and crosspolarization.

I. Introduction

A KNOWLEDGE of the reflectivity of natural and artificial materials is important for the design of remote-sensing systems including radars and radiometers. This is needed in order to get an impression of possible target reflectivities, and also the performance of some artificial materials like absorbers or dielectrics is of extreme importance for the design of these systems.

In the submillimeter-wave range most of the reflectivity measurements are carried out using Fourier-transform spectrometers (FTS) which are related to IR measurement techniques (Afsar *et al.* [1]). The measurement procedure comprises the data sampling, the Fourier transformation and filtering of the data and thus only can be carried out in a laboratory. Unfortunately an improvement in the frequency resolution directly leads to increased spectrometer dimensions.

Our approach, however, is not related to the IR range but to conventional microwave remote measurement techniques such as radar systems (Currie *et al.* [2]). The measurements can therefore in principle be carried out outdoors. Additionally the system delivers reflectivity data in real time and its resolution is only limited by the bandwidth of the transmitter oscillator and the IF-filters.

Gaussian optics were used to design the transmitter/receiver optics platform. In contrast to most other submillimeter-wave systems which consist of a fixed optical circuitry our system employs a "chessboard"-like platform on which the optical circuit is realized according to the desired measurement task. The design of such a system and its application to the heterodyne dual-polarization reflectometer is described in the following.

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II. The Reflectometer System

2.1 Quasi-Optical Design

The basic idea of a flexible quasi-optical setup was developed by Martin [3] and Lesurf [4] and was already tested at lower frequencies. In our approach, we extend its application to the submillimeter-wave range and to heterodyne measurement techniques.

The measurement setup consists of three major parts: a transmitter source, a local oscillator system and the base platform where the quasi-optical signal processing is carried out. A carcinotron (backward-wave oscillator) is employed as the transmitter source. It is tunable in frequency from 550 to 610 GHz and delivers a maximum output power of 4.8 mW coupled out with a dual-mode horn. To provide monomode operation a tapered waveguide section is inserted between the multimode output of the Carcinotron and the horn antenna. The local oscillator system consists of a molecular gas laser which is optically pumped by a CO_2-Laser. The actual submillimeter wavelength depends upon the laser medium which in our case is formic acid (HCOOH). The output power is 1.5 mW at a wavelength of 513 μm (584.4 GHz). Both powers were measured using a calibrated quasi-optical power meter [5].

In Gaussian beam technology a wave is guided by lenses or mirrors which refocus the beam periodically. A reduction of the number of focussing elements per unit distance directly leads to a reduction of the loss of this waveguide type as, for example, a lens has a typical loss of 1 dB at 600 GHz. An optimization of such a beam waveguide can be achieved as described in the following [3]:

The distance d that a given Gaussian beam with radius $w = w_L$ at a lens can travel before it spreads to w_L again is dependent upon its phase front curvature ρ (in the plane, where w_L is measured) and the wavelength λ. From the Gaussian beam formulas (e.g., Goldsmith [6]) one easily derives that with

$$\rho = \frac{\pi w_L^2}{\lambda} \tag{1}$$

one reaches a maximum distance

$$d_{MAX} = \frac{\pi w_L^2}{\lambda} \tag{2}$$

before the beam spreads to w_L again and where it has to be refocused.

If we now choose the focal length f of a lens to be $d_{MAX}/2$ and the distance between two consecutive lenses to be d_{MAX} then we get a beam waveguide where we have the minimum loss per unit distance. Provided the input beam waist lies in the focal plane of the first lens and its radius w_0 is either constant or proportional to the wavelength λ, we also have frequency independence of every second of the following beam waists [6].

Between two consecutive lenses we can place quasi-optical signal processing components like mirrors, wire-grid polarizers, dielectric sheets or metallic meshes and components which are composed of these elements, like attenuators, diplexers and filters. Thus by arranging lenses and other components in the described way we can build up optimized quasi-optical circuits.

To achieve a highly flexible setup, focussing elements and components are each mounted on separate square subplatforms which can then be arranged on a "chessboard"-like base platform. Each subplatform has the sidelength U. Fig. 1 shows that we have between two lenses N free square elements of sidelength U plus two times half an element for the lens subplatform:

$$d_{MAX} = (N + 1)U \tag{3}$$

This design differs from the setup described by Lesurf [4] who employed right-angled triangles as subplatforms. However we found that the latter form imposes mechanical difficulties with reflective optics which have to be adjustable in the submillimeter-wave range.
With

$$D = Bw_L \tag{4}$$

we determine the lens diameter D which is necessary in order not to truncate the beam. B should be not less than 3 but if the size restrictions are not too stringent, a value of 5 would be more appropriate (Ediss [7]). Further

$$C = \frac{U}{D} \tag{5}$$

gives respect to the extra space needed for the mechanical fixture of the components. Thus:

$$d_{MAX} = (N + 1)CD \tag{6}$$

and with (4) and (3):

$$w_L = \frac{\lambda}{\pi}(N + 1)CB \tag{7}$$

$$D = \frac{\lambda}{\pi}(N + 1)\ CB^2 \tag{8}$$

$$U = \frac{\lambda}{\pi}(N + 1)C^2B^2 \tag{9}$$

$$d_{MAX} = \frac{\lambda}{\pi}(N + 1)^2C^2B^2. \tag{10}$$

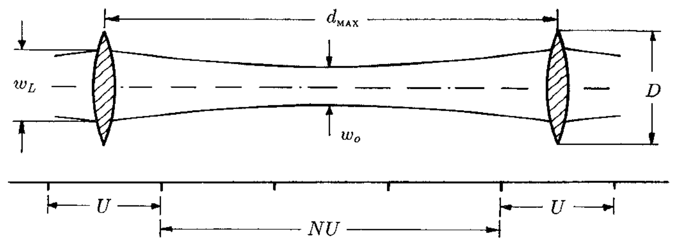

Fig. 1. Beam propagation on the flexible submillimeterwave measurement setup.

TABLE I
CONSTRUCTION PARAMETERS OF THE FLEXIBLE SUBMILLIMETERWAVE MEASUREMENT SETUP

Base-Platform (Elements)		1040 mm × 560 mm (13 × 7)
Subplatform-Sidelength	U	80 mm
Lens Spacing	d_{MAX}	320 mm
Lens Diameter	D	45 mm
Focal Length	f	160 mm
Free Elements	N	3
Beam Waist Radius	w_0	5.13 mm
Beam Radius (at the lenses)	w_L	7.26 mm

For the determination of these coefficients we have taken account of special requirements of the setup and of the measurement task. In order to have maximum flexibility the whole measurement setup was oversized. For example, B was chosen to be 6 as this large value allows the design of interferometer diplexers with extremely low non-overlap loss, i.e., ultra-broadband submillimeter-wave devices. Other restrictions were given by already existing subcomponents like wire-grid polarizers. With $N = 1$ we get the smallest possible system. N was chosen to be 3, however, as a lower value results in thick, aspheric beam waveguide lenses with high absorptive losses. Table I summarizes our construction parameters.

In addition to the standardized lenses, beam-matching transformers are required to optimally adapt the standard beam to other quasioptical systems situated at the input and output ports of the board. For our reflectometer we need four different lens-type matching transformers:

1. For the transformation of the laser beam into the beam waveguide mode.
2. For the matching of the field of the dual-mode horn at the Carcinotron tube to the beam waveguide mode.
3. For the coupling of the beam waveguide mode to the Schottky-diode mixer's whisker antenna.
4. For the beam shaping of the transmitting beam.

Note that 2. and 3. require thick, i.e., aspheric lenses while for 1. and 4. spherical lenses are sufficient.

With the described setup many quasi-optical circuits can be realized. A limitation is given only by the number of components available and in the size of the base platform. The greatest advantage, however, is that no more beam calculations are required: setting up a circuit only requires "counting" free spaces and plugging in the components at the appropriate places. This takes only a few minutes. The heterodyne dual-polarization reflectometer is an example of a rather complicated setup. The following section gives an idea of how it works and also how to build it in this flexible way.

2.2 Circuit Design

Fig. 2 shows the quasi-optical circuitry for the heterodyne polarimetric reflectometer and Fig. 3 displays a photo of the realization of the flexible measurement setup. The beam of the carcinotron transmitter source is coupled into the beam waveguide via the input coupling lens ICL1. After passing the lens BWL1 the beam is deflected and is guided via BWL2 and BWL3 to the transmitter lens TL1 where the beam leaves the platform. Note that the transmitted beam is polarized perpendicular to the platform.

The sample S is placed at the beam waist (radius 12 mm) to provide approximately plane wave conditions. Thus in the case of a plane metallic reflector 100% of the incident power is coupled back to the reflectometer. After being reflected (or scattered) from the sample a part of the power returns to the platform, passes TL1, and is then guided to the input ports of the two receiver channels depending on their polarization.

The copolarized part is guided via the 3 dB-dielectric beam splitter DBS1 to the Martin-Puplett-Diplexer MPD1 which consists of a vertical polarizer VP1, a diagonal polarizer DP1, a fixed rooftop mirror RM1 and a movable rooftop mirror MRM1 which is driven by a stepper motor. Here the signal beam is combined with the LO beam.

It cannot be avoided that a part of the power passes DBS1 and returns to the carcinotron. However, the lenses ICL1, BWL1,2,3, TL1 and the dielectric beam splitter DBS1 provide a two-way attenuation of approximately 16 dB which is enough to isolate the carcinotron. An additional attenuator which consists of HP1, TP1 and HP2 may be used for leveling the power when measuring at different frequencies.

Mixing is performed in an open structure Schottky-diode mixer SM1 which is equipped with an ultra-broadband IF output coupling structure [8] thus allowing use of the whole carcinotron tuning range.

For the crosspolarized part of the reflected wave it is essentially the same: the horizontal polarizer HP3 guides the power to MPD2.

The LO beam itself is also polarized perpendicular to the platform. For use in MPD1 the polarization of the LO beam has thus be turned by 90° in the polarization rotator PR1.

Finally, the power and the frequency at the IF ports of the two Schottky-diode mixers are measured using a spectrum analyzer. We define the reflectivity R to be

$$R = \frac{P_e}{P_i} \tag{11}$$

where P_i is the power incident on the sample and P_e is the power emerging from the sample in the direction of the incident beam. Similarly the return loss is defined as

$$^{l}R = 10 \log \left\{ \frac{P_e}{P_i} \right\}. \tag{12}$$

The return loss was then determined with respect to a polished aluminum plate for the copolarized part, i.e., we assumed P_e to be equal to P_i for this special sample. For the copolarized part a wire grid, which was turned to 45°, was taken as a reference resulting in $P_e = \frac{1}{2} P_i$.

The dynamic range of the measurements was 44 dB in copolarization and 40 dB in crosspolarization. A frequency modulation of the carcinotron frequency of about ±5 MHz, caused by the high-voltage power supply, resulted in amplitude fluctuations of the transmitter beam. This error reduced the measurement accuracy to ± 0.5 dB.

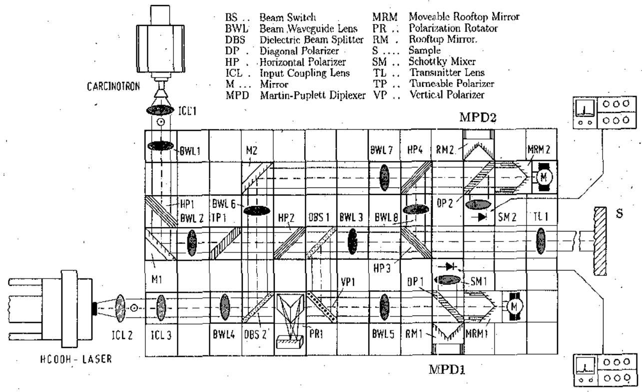

Fig. 2. Circuit diagram of the polarimetric heterodyne reflectometer.

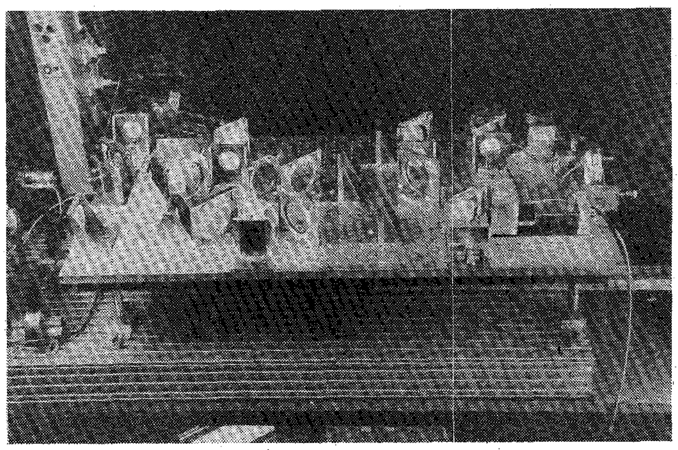
Fig. 3. Photography of the polarimetric heterodyne reflectometer on the flexible quasi-optical measurement setup.

III. Reflectivity Measurements

First we measured the reflectivity of different dielectric slabs because they can be used as reflectivity standards and are therefore useful to test the setup. On the other hand the return loss of a dielectric lens is an important figure for the design of quasi-optical submillimeter-wave

TABLE II
MEASURED REFLECTIVITIES OF NATURAL AND ARTIFICIAL MATERIALS AT 580 GHz

	Copolarization		Crosspolarization	
	$R/\%$	$'R/\mathrm{dB}$	$R/\%$	$'R/\mathrm{dB}$
Teflon	6.7	−11.7		
Polyethylene	4.7	−13.2	0.71	−30
TPX	2	−16.9		
Fused Silica	4.7	−13.2		
eccosorb AN 77:				
T = 290 K	0.05	−33	0.04	−34
T = 77 K (under 20 mm LN_2)	0.016	−38	0.01	−40
T = 77 K (cooled from backside)	0.06	−32	0.05	−33
IR-Absorptive Paint on Metal	75	−1.2		
Heat-Resistive Black Paint on Metal	14	−8.5		
Oak Wood	15	−8.2		
Water	15.8	−8	3.16	−15
Sand (dry)	0.16	−28	1.6	−18
Sand (wet)	0.25	−26	1.0	−20
Sand (1 mm) on Metal	0.63	−22		
Franconian Soil (regional soil, sandy)	0.16	−28	1.6	−18

systems. The results lay well within ± 10% of the expected values.

Nevertheless the finite thickness of the slabs causes standing wave effects which were the reason for the tolerances. As the thickness could not be determined within a few micrometers the error became too large for a precise measurement. For reflectivity measurement of dielectrics with low transmission loss it is therefore more appropriate to use prism-shaped samples, but good results were obtained with high-absorptive dielectrics. To verify the linearity of the reflectometer, however, we used wire grid polarizers turned to the appropriate angle relative to the transmitter polarization to result in a well-defined reflectivity in the co- and crosspolarization.

Next we were interested in the performance of absorbers in this frequency range. As an example, eccosorb was measured at room temperature and at 77 K (liquid nitrogen). This could be of interest for the design of hot and cold loads in radiometer systems. We found that the reflection loss increases with about 20 mm of liquid nitrogen over the absorber. A decrease of the reflection loss occurs when the eccosorb is cooled from its backside thus resulting in a thin ice layer on the surface. Nevertheless we found a good performance in this frequency range.

Certain samples of IR-absorptive paint on metal however, which should have return losses on the order of −20 dB at 10 μm showed reflectivity values of 75% which corresponds to a return loss of only −1.2 dB.

Finally we measured some natural materials like wood, sand, water and soil of the region. To measure the latter ones the beam emerging the transmitter lens was vertically deflected by an additional 45°-mirror. It is interesting that most of the natural materials showed return losses in the −20 dB range which is quite different from results received at millimeter wavelengths. A complete set of measured reflectivity data is presented in Table II.

IV. CONCLUSION

A flexible quasi-optical measurement setup was designed which allows to carry out a great variety of measurement tasks in the submillimeter-wave region.

With this system a new reflectometer concept for the submillimeter-wave region was realized. This concept has proven to be useful for the measurement of different materials and for future tasks in radar engineering and environmental protection.

Interesting reflectivity behavior of different materials show the importance of continuing the work in this field.

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